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Research Article

Thematic mapping of biosecurity highlights divergent conceptual foundations in human, animal, plant and ecosystem health

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Abstract

Effective biosecurity policies are essential to address several major sociological and environmental challenges facing humankind including existential pandemic risks, threats to food security, loss of ecosystem services and public resistance to pesticides and vaccines. Yet biosecurity is subject to multiple interpretations that include dealing with the threats from bioterrorism, managing laboratory biosafety to prevent the escape of pathogenic organisms, handling food and agricultural production systems to prevent disease introduction and addressing the threat of introduced organisms to flora, fauna and humans. The absence of a shared vision of what biosecurity encompasses means that decision-makers are often challenged to design appropriate biosecurity policies at national and global scales. The design of effective policy strategies requires an understanding of the methodological and conceptual barriers that constrain attempts to build an interdisciplinary approach to biosecurity. Here, the first thematic map of the biosecurity research landscape is undertaken to assess just how diverse the interpretation of biosecurity is amongst the global research community and the extent to which the articles published since 2000 represent a common conceptual foundation or are largely clustered within sectors. Co-citation, bibliographic coupling and co-word analyses highlighted that the field of biosecurity encompasses a wide range of domains from biochemistry through to political science, but the research supporting different sectors largely draws from a distinct literature base. While ecosystem and plant health were clustered together within the broad grouping of biological invasions, there was a clear separation from both human and animal health. Yet, there is considerable scope for the management of biological invasions to benefit from insights derived from social perspectives in human and animal health. Biosecurity remains divided by conceptual differences and specialised vocabularies that limit the effectiveness of biosecurity policies addressing biodiversity conservation, public health and food security. To overcome these constraints requires the building of a global biosecurity community that accepts a broader definition of biosecurity, avoids sectorial jargon and establishes mechanisms to cultivate interdisciplinarity through specialised collaborative centres, cross-sectorial research programmes and conceptually rich training programmes.

Key words: Epidemiology, invasive alien species, One Biosecurity, One Health, pests, social network analysis, surveillance, zoonoses

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Introduction

The term biosecurity has become increasingly popular within the scientific literature in the last two decades pointing to a greater focus on this topic, particularly following the SARS-CoV-2 pandemic in 2019 (Fig. 1). Despite the increasing use of this term, multiple definitions of biosecurity can be found in standard reference texts (Table 1). Biosecurity is variously defined in terms of dealing with the threats

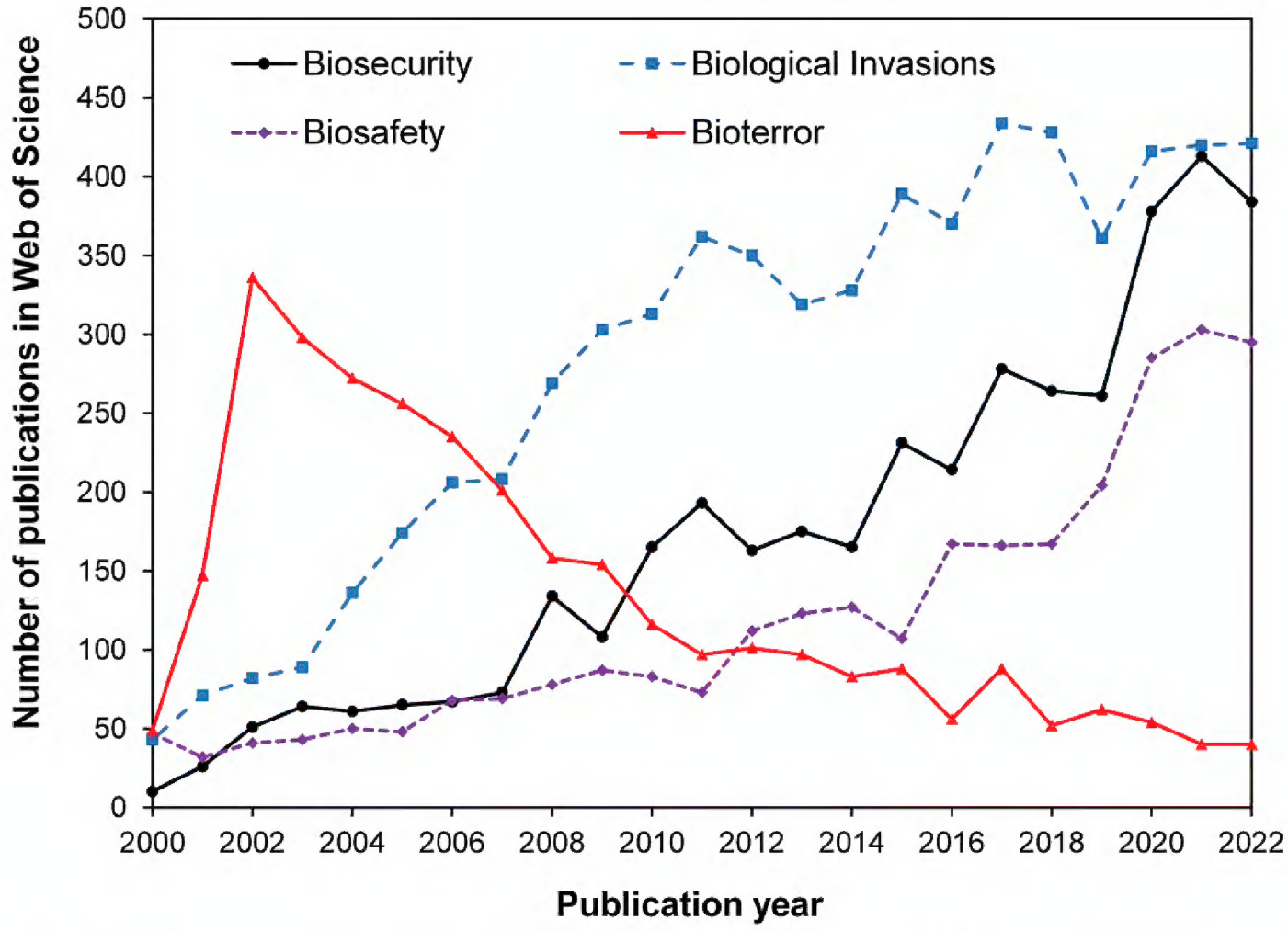

Figure 1. Temporal trend in the number of articles archived in Web of Science and published between 2000 and 2022 that include biological invasion, biosafety, biosecurity or bioterror (including bioterrorism and bioterrorist) in the article title, author keywords or Keywords Plus. The figure illustrates the relative growth in interest in biosecurity compared to the other terms over the last two decades.

Table 1. Definitions of the term biosecurity as published in several Oxford dictionaries by Oxford University Press. The name of the dictionary and its description of biosecurity are provided.

Oxford dictionary	Description
Biomedicine (Lackie and Nation 2019)	Describing methods or procedures designed to prevent harm from pathogenic organisms that are being handled for experimental purposes.
Agriculture & Land Management (Manley et al. 2019)	A series of planned measures introduced to a farm or enterprise concerned with food production that minimises the risk of accidental disease introduction.
Human Geography (Rogers et al. 2013)	The security of a country's human population, flora and fauna against the unwanted introduction of various biological phenomena (such as viruses, toxins, insects, plant species and mammals).
Environment and Conservation (Park and Allaby 2017)	Biological security, particularly protection against bioterrorism and the use of biological weapons.
Geography (Mayhew 2023)	The protection of people and animals from pests and infectious diseases, notably by managing the movement of agricultural pests and diseases, reducing the effects of invasive species on supposedly indigenous flora and fauna and preventing the purposeful and inadvertent spreading of biological agents into the human population.
Advanced Learner's (Hornby 2010)	The activities involved in preventing the spread of animal and plant diseases from one area to another.
Concise English (Stevenson and Waite 2011)	Measures taken to protect the population against harmful biological or biochemical substances.
English (oed.com)	Protection against the incursion or escape of potentially harmful or undesirable organisms, especially pathogens.
New Zealand English (Deverson and Kennedy 2005)	Procedures followed or measures taken to safeguard the flora and fauna of a country etc. against exotic pests and diseases.
American English (Stevenson and Lindberg 2010)	Procedures intended to protect humans or animals against disease or harmful biological agents.

from bioterrorism, managing laboratory biosafety to prevent the escape of pathogenic organisms, handling food and agricultural production systems to prevent disease introduction and addressing the threat of introduced organisms to flora, fauna and humans. The confusion as to the definition of biosecurity also exists at an international level. Even within the United Nations (UN), separate specialised agencies that have oversight of pest and/or disease outbreaks use different defini-

tions. The UN Food and Agriculture Organisation defines biosecurity as a strategic and integrated approach to analysing and managing relevant risks to human, animal and plant life and health and associated risks to the environment (FAO 2007). In contrast, the World Health Organisation views biosecurity as synonymous with biosafety and it is limited to approaches to prevent the unauthorised access, loss, theft, misuse, diversion or release of pathogenic biological agents (WHO 2020). The World Organisation for Animal Health has a more specific definition of biosecurity as a set of management and physical measures designed to reduce the risk of introduction, establishment and spread of animal diseases, infections or infestations to, from and within an animal population (Renault et al. 2021). This lack of a consistent definition may be the reason that, in its guidance for negotiators of multilateral environmental agreements, the United Nations Environment Programme provides definitions for biosafety and alien species, but not for biosecurity (UNEP 2007).

The lack of a standard definition of biosecurity is much more than simply an etymological problem. Without a shared vision for what biosecurity encompasses, decision-makers are challenged to design appropriate biosecurity policies at national and global scales (Meyerson and Reaser 2003). There are clearly different perspectives amongst sectors (e.g. agricultural, environmental, medical, military) that will lead to divisions amongst those who view biosecurity as a laboratory biosafety issue, a means to combat bioterrorist threats, an approach to better manage farm hygiene, tools to prevent incursions of pests and diseases harmful to agriculture or measures to mitigate a major driver of biodiversity loss and ecosystem change. This diversity of views can lead to a fragmented approach to biosecurity in terms of policy coverage, education and training, as well as research investment. The absence of a consensus view is also a major stumbling block for any attempts to establish an overarching global One Biosecurity convention that would simultaneously address biological invasions that threaten human, animal, plant and ecosystem health (Hulme 2021).

While attempts to derive a universal definition of biosecurity are certainly worthwhile (Meyerson and Reaser 2002b), such a top-down approach may fail to account for sectorial differences in how biosecurity is perceived and implemented amongst the diverse human, animal, plant and ecosystem health research community. Progressing consensus within the research community as to what biosecurity means is a crucial step in delivering a cohesive evidence base that supports policy-makers to deliver better integrated biosecurity policies (Hulme 2021). Consensus is also essential to address several major sociological and environmental challenges impacting on biosecurity, such as climate change, increasing urbanisation, agricultural intensification, human global mobility, loss of technical capability as well as public resistance to pesticides and vaccines (Hulme 2020).

The design of effective policy strategies requires an understanding of the methodological and conceptual barriers that constrain attempts to build an interdisciplinary approach to biosecurity and these obstacles are strongly connected to the nature of scientific practice and the limits of human cognition (MacLeod 2018). Knowledge of the scientific landscape, its conceptual foundations, emerging ideas and vocabulary can provide insights into these cognitive barriers. Here, the first scientific map (Chen 2017; Chen and Song 2019) of biosecurity is undertaken to assess just how diverse the interpretation of biosecurity is amongst the global research community and the extent to which the science represents a

common corpus of knowledge or is largely clustered within sector specific siloes. The analysis aimed to:

1. Capture the breadth of disciplines associated with biosecurity research.
2. Characterise the dominant conceptual themes examined within the research corpus.
3. Describe the extent to which the research is coupled across different sectors.
4. Identify the cognitive barriers preventing an interdisciplinary approach to biosecurity.

These findings are then used to explore how research underpinning biosecurity can be made more interdisciplinary and identify unifying principles that are common to different disciplines, but where there is currently little cross-fertilisation.

Methods

Data retrieval

Bibliographic data were extracted from the Web of Science Core Collection of Citation Indexes (which includes science, social sciences, arts and humanities citation indexes) for research articles, reviews, conference proceedings, book chapters, editorial material and letters relating to the single search term – biosecurity - published during the 23-year period from January 2000 to December 2022 inclusive (accessed on 6 June 2023). To ensure the search only extracted the most relevant articles, the fields mined in the search were restricted to the title of the article, author-defined keywords and Keywords Plus. Keywords Plus is a set of keywords automatically generated by Web of Science from the cited bibliography that is claimed to capture an article's content with greater depth and clarity than author-generated keywords (Garfield and Sher 1993). The use of author-defined keywords together with Keywords Plus is an effective way to capture the knowledge structure of scientific fields as well as an article's content (Zhang et al. 2016; Hulme 2022). The full record, including cited references, was downloaded for each article retrieved and imported into the specialist software tool VosViewer 1.6.19 for constructing and visualising bibliometric networks (van Eck and Waltman 2010; van Eck and Waltman 2014).

Thematic mapping

The Web of Science assigns each journal, book or conference proceedings to one or more of 252 Research Areas (hereafter described as WoS Research Areas) in science, social sciences, arts and humanities and is generally considered the best high-level classification scheme for detailed bibliometric analysis (Milojević 2020). While many bibliometric studies simply tally the most frequently represented research areas, such an approach fails to capture levels of interdisciplinarity since many journals are assigned to multiple categories. Thus, for a more effective high level thematic map, the co-occurrence of different WoS Research Areas assigned to individual articles was visualised as a network to distinguish distinct thematic areas.

Although there are different ways to assess the connectivity with a corpus of research articles (Enders et al. 2019; Staples et al. 2019; Muñoz-Mas et al. 2021), a comparison of co-citation and bibliographic coupling provides an effective means

to map the underlying relational structure amongst research articles (Donthu et al. 2021). Co-citation analysis quantifies the frequency with which two different articles are both independently cited by one or more articles, such that the more publications that cite these two articles, the stronger their co-citation (Small 1973). Bibliographic coupling measures how often two articles cite the same third article indicating that they may cover the same topic and the more common references they share, the stronger their coupling strength (Jarneving 2007). These two methods provide different, but complimentary insights into the thematic structure of scientific literature since co-citation describes the linkages amongst cited publications to understand how the main themes in a research field have developed, whereas bibliographic coupling describes the relationships amongst citing publications to provide insights into current development of the field (Boyack and Klavans 2010; Kleminski et al. 2022).

Co-word analysis examines the co-occurrences of keywords to explore the existing relationships amongst topics in a research field by focusing on the written content of the publication itself to build a conceptual structure of the domain (Donthu et al. 2021). This semantic map helps to understand the cognitive structure of a research field, but assumes that the concepts behind co-occurring words are closely related (Zupic and Čater 2015). Both author-defined keywords and those generated by the Keywords Plus algorithm were extracted from each article retrieved and assumed to be the key description of its research content. The list of keywords was reviewed and simplified by standardising across synonyms, abbreviations and acronyms as well as alternative spellings of words. Generic terms such as science, biology, program etc. were ignored as were keywords relating to a specific country or region. Finally, given that the initial search term was biosecurity, this word was excluded from the co-word analysis.

Visualisation

In the cases of both co-citation and bibliographic coupling, only those articles that had received at least 10 citations were included in the analyses to avoid arbitrary clustering associated with infrequently cited articles. Fractional-, rather than full-counting was implemented since it has been shown to produce better balance and consistency in bibliometric indicators by reducing the influence of highly-cited articles and those with large bibliographies (Perianes-Rodriguez et al. 2016; Szomszor et al. 2021). To ensure dominant themes were captured, co-word analysis included only keywords that occurred five or more times and full-counting was implemented. For the analysis of WoS Research Areas, all articles were included and full-counting was implemented. For all four analyses (WoS Research Areas, co-citation, bibliographic coupling and co-word analysis), association strength was selected as a probabilistic-based similarity measure to normalise the maps for visualisation. The association strength compares the number of observed co-occurrences between two entities (e.g. articles, keywords or WoS Research Areas) against the null expectation of co-occurrences being randomly distributed to give an indication how strong the relationship is between a pair of entities (Steijn 2021). Association strength is particularly suited for bibliometric analysis and has the advantage of detecting highly-cited articles regardless of citation traditions in different disciplines (van Eck and Waltman 2009). The total strength of the citation links of a given article with other publications (total link strength or weighted degree) was applied as a weight. Articles were clustered using a smart local moving algorithm to

identify community structures with higher modularity values (Waltman and van Eck 2013) and depicted using the visualisation of similarities distance-based mapping technique that has been shown to produce better structured thematic maps than alternatives such as multidimensional scaling (van Eck and Waltman 2010).

Network metrics

There are many different measures of network centrality that provide an indication of the relative importance of a particular node within a network, but they are rarely used in an a priori approach to describe different types of networks (Rodrigues 2019). Three different measures of network centrality were used to capture the relative importance of WoS Research Areas, citation (whether co-citation or bibliographic coupling) and co-word networks. Betweenness centrality was selected as the best measure of WoS Research Area importance since it identifies nodes that act as bridges across different parts of the entire network and hence a WoS Research Area with high betweenness centrality is likely to be the most interdisciplinary and thus crucial to the interconnectedness of a network (Leydesdorff 2007). In contrast, eigenvector centrality was used to identify important articles in both co-citation and bibliographic coupling networks since it provides a measure of node influence since articles with high eigenvector centrality will themselves be linked to other articles that have many connections (Diallo et al. 2016). Finally, the most important keywords were identified as those with the highest harmonic closeness centrality since this indicates which words are most closely associated with other words and, thus, likely to be most representative (Choudhury and Uddin 2016). Centralities measures were calculated using the Gephi 0.1 network software (Bastian et al. 2009).

Results

A total of 3,685 articles were retrieved by the title, author-defined keyword and Keywords Plus search for the term biosecurity. This corpus encompassed 115 out of a possible 252 WoS Research Areas, but the vast majority (91.6%) of the retrieved articles were captured by only 23 WoS Research Areas. The primary WoS Research Areas as determined by the number of articles retrieved were Veterinary Sciences (1,011 articles), Environmental Science & Ecology (540), Agriculture (483), Biodiversity & Conservation (257), Public, Environment & Occupational Health (222) and Science & Technology (204). These top 23 WoS Research Areas described five marked clusters (Fig. 2) that map on to animal health (e.g. Veterinary Sciences, Infectious Diseases), plant health (e.g. Agriculture, Food Security and Plant Science), ecosystem health (e.g. Environmental Sciences, Biodiversity and Conservation), a socioeconomic cluster (e.g. Public Health, Social Sciences, Government and Law) and a technology cluster (e.g. Science and Engineering). Environmental Science & Ecology was the WoS Research Area with by far the highest betweenness centrality (0.238), followed by Veterinary Sciences (0.095), while Engineering (0.00) was the least important and was relatively isolated from other nodes (Fig. 2).

Almost one quarter (841 or 22.8%) of the articles cited by the retrieved literature were co-cited at least 10 times, with the earliest article being published in 1921 (Montgomery 1921). The co-citation network comprised 37,770 edges linking the 841 nodes and was strongly modular with four distinct clusters identified (Fig. 3a). The largest cluster (364 articles) comprised articles addressing biological

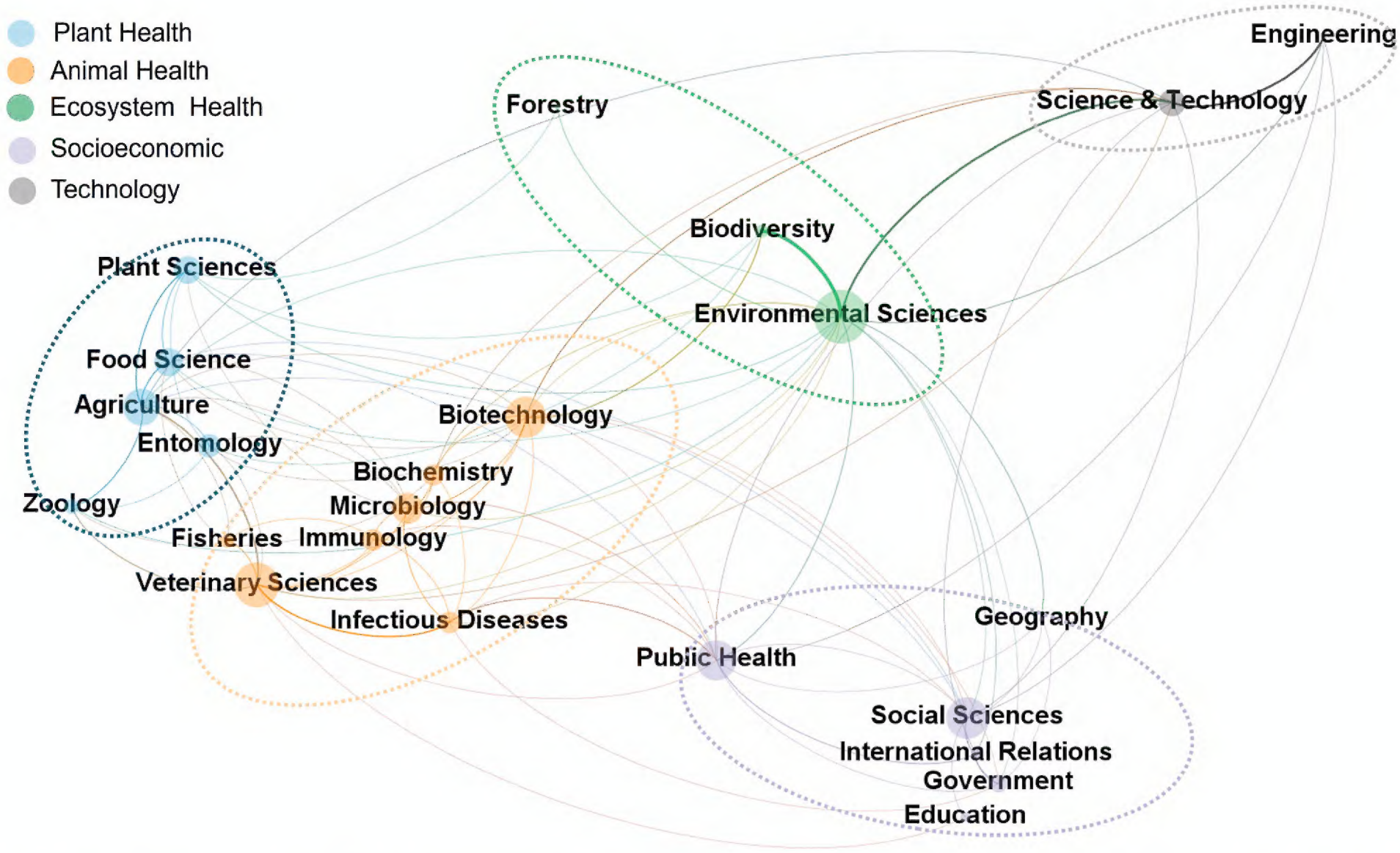

Figure 2. Thematic map of 23 Web of Science Research Areas that encompass over 90% of all articles in the biosecurity corpus. The relative number of publications that fall under each WoS Research Area (size of circles) and the strength of the links between them (line thickness) are displayed. Five clusters can be identified and are highlighted by the ellipses.

invasions relating to both plant and ecosystem health with the top three journals being Biological Invasions, Trends in Ecology & Evolution and Frontiers in Ecology and Environment. The second cluster (331 articles) included primarily articles within the field of animal health as described by the top three most frequently occurring journals (Preventive Veterinary Medicine, Transboundary and Emerging Diseases and Veterinary Clinics of North America: Food Animal Practice). Socioeconomic perspectives were represented by the third cluster (104 articles) with an emphasis on rural livelihoods relating to farming as seen in the top three journals: Environment and Planning A: Economy and Space, Sociologia Ruralis and Transactions of the Institute of British Geographers. The smallest cluster (42) dealing with human health in relation to pathogens and biosafety as published in Nature, Science and World Health Organisation reports. The five most influential articles, as determined by their eigenvector centrality were all related to aspect of biological invasions whether specifically addressing the biosecurity system and its components (Meyerson and Reaser 2002a; Waage and Mumford 2008) or more specifically in terms of the role of trade (Hulme 2009), introduction pathways (Hulme et al. 2008) and economic costs (Pimentel et al. 2005).

Over one of third of articles met the criteria for bibliographic coupling (1,359 or 36.87%) with 43,490 links between them. The network analysis revealed broadly similar trends as for co-citations, but with greater granularity revealing ten rather than four distinct article clusters (Fig. 3b). Three clusters were strongly aligned to animal health, with differences amongst them relating to the livestock concerned whether cattle and pigs, poultry or horses. Preventive Veterinary Medicine was amongst the top three most frequently occurring journals in each of these three

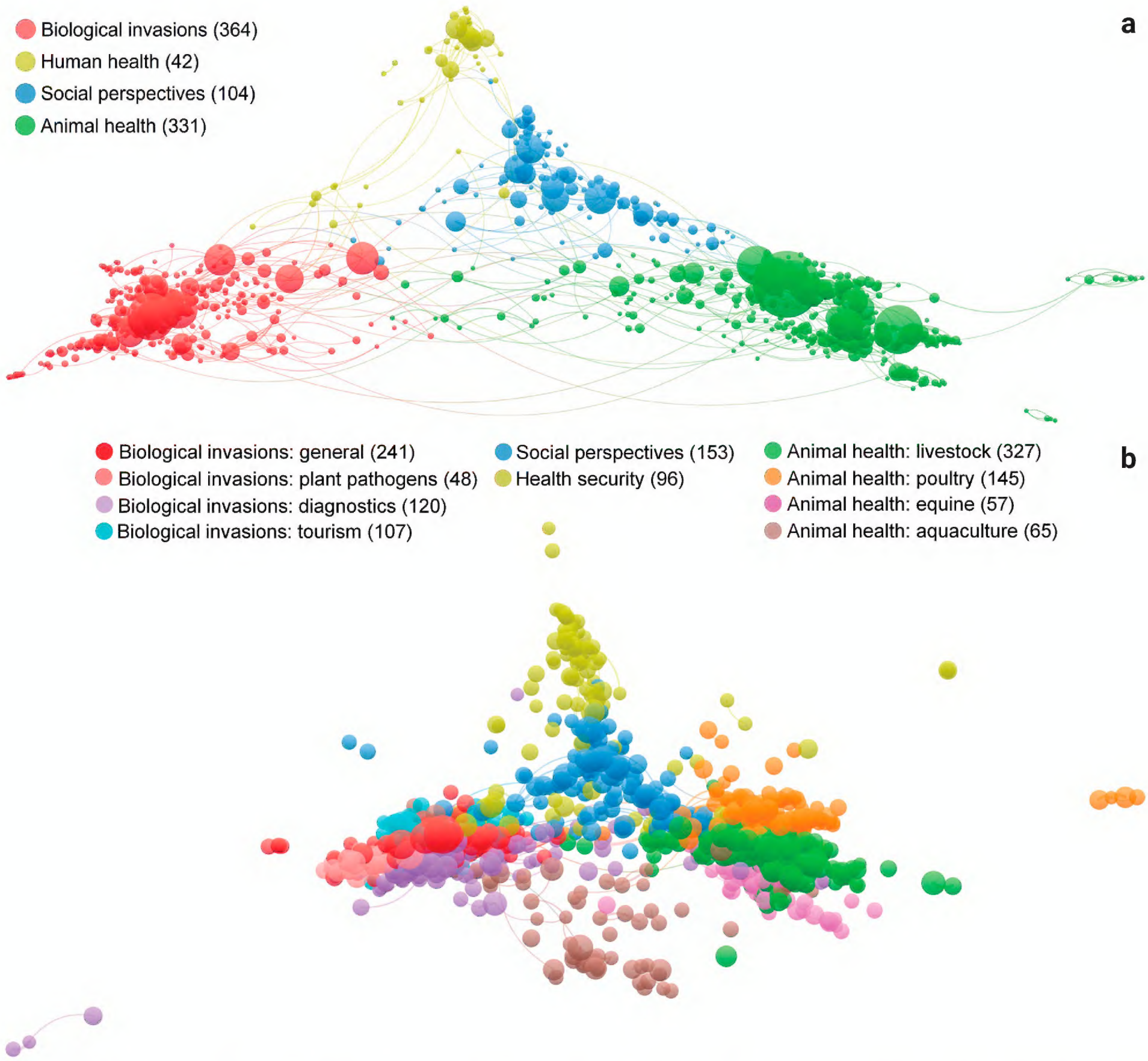

Figure 3. Visualisation of: **a** co-citation and **b** bibliographic coupling of the corpus of articles retrieved using search term biosecurity in titles, author keywords or Keywords Plus published between 2000 and 2022. The two analyses share a similar topology with four clusters identified in co-citation analysis and ten in the bibliographic coupling. Each cluster has been given a representative description and the number of articles in each cluster are presented within parentheses.

clusters. A further three clusters were aligned to pest, pathogen and weed invasions in both semi-natural and agricultural ecosystems. Amongst these, the largest cluster related primarily to the theme of biological invasions with over 10% of the articles being published in Biological Invasions, while the three other clusters were characterised by studies of introduction pathways (e.g. Management of Biological Invasions), plant pathology (e.g. Plant Pathology) and molecular diagnostics (e.g. Molecular Ecology Resources). A discrete human perspectives cluster was also still evident that reflected a similar composition to the co-citation analysis with journals dealing with rural studies being prominent (e.g. Environment and Planning A: Economy and Space, Journal of Rural Studies). Rather than being directly associated with human health, a further cluster was comprised largely of articles in journals that focused on health security and bioterrorism (e.g. Frontiers in Bioengineering and Biotechnology). The final cluster appeared to bridge across the animal health

and biological invasions clusters and mostly encompassed journals addressing aquaculture both from a production perspective, but also in terms of risks of invasion (e.g. Aquaculture, Journal of the World Aquaculture Society). The five most influential articles as determined by their eigenvector centrality were reviews that addressed human perceptions (Cliff and Campbell 2012), communication (Hanrahan and Melly 2019) and awareness (Klapwijk et al. 2016) of invasive alien species or general syntheses of biological invasions (Russell et al. 2017; Cope et al. 2019).

Across both author-defined keywords and those generated by the Keywords Plus algorithm, a total of 5,804 distinct terms were retrieved, of which 308 occurred sufficiently frequently (more than five times) to be analysed further (Fig. 4). Four clusters of terms were identified with once again a clear distinction between terms characterising animal health (e.g. infection, transmission, epidemiology) from those that related to biological invasions (e.g. surveillance, spread, invasive alien species). A further discrete cluster related to terms describing emerging human health threats from pathogens (e.g. disease, virus, infectious disease). A final cluster captured human responses to biosecurity threats and, as a result, spanned both the animal health and biological invasions cluster since the most central terms in this cluster were relevant to both areas as well (e.g. management, prevention, policy).

Clear differences were found in the most frequent keywords associated with the four clusters (Table 2). The biological invasions cluster is strongly shaped by terms associated with the invasion continuum (e.g. spread, impact), major pathways of

Table 2. The 25 most frequent keywords in each of the four clusters identified through co-word analysis: biological invasions, animal health, human risks and response.

Count	Biological invasions	Count	Animal health	Count	Human risks	Count	Response
360	invasive alien species	303	pigs	320	virus	345	management
284	biological invasion	269	poultry	311	disease	142	farmer
211	surveillance	260	cattle	130	biosafety	132	prevention
190	impact	237	transmission	118	biowarfare	116	veterinary
165	spread	220	infection	84	infectious disease	111	policy
140	eradication	189	avian influenza	80	covid-19	108	perceptions
126	trade	157	epidemiology	63	public health	100	risk management
123	risk assessment	138	antimicrobial resistance	59	agriculture	90	knowledge
109	pathogens	131	outbreak	58	influenza	88	attitude
105	climate change	123	foot and mouth disease	53	dual use research	86	behaviour
101	polymerase chain reaction	118	dairy	39	One Health	72	strategies
100	quarantine	114	vaccination	34	food	64	decision-making
96	biodiversity	104	salmonella	33	challenges	61	animal health
94	identification	103	farm	33	human	57	bovine tuberculosis
89	plant disease	95	herds	31	global health security	46	animal disease
88	risk analysis	82	equine	30	pandemic	41	communication
87	dispersal	78	livestock	25	globalisation	38	environment
79	pathway	71	epidemic	22	preparedness	38	information
77	pests	67	disinfection	19	ebola	38	uncertainty
76	threat	65	zoonoses	15	capacity building	29	stakeholder
70	populations	64	*Escherichia coli*	14	husbandry	23	wildlife
67	transport	63	respiratory disease	14	migration	22	participation
65	conservation	62	African swine fever	11	cyberbiosecurity	21	badgers
57	aquaculture	62	campylobacter	11	swine influenza	18	awareness raising
53	costs	55	bacteria	10	bat	16	compliance

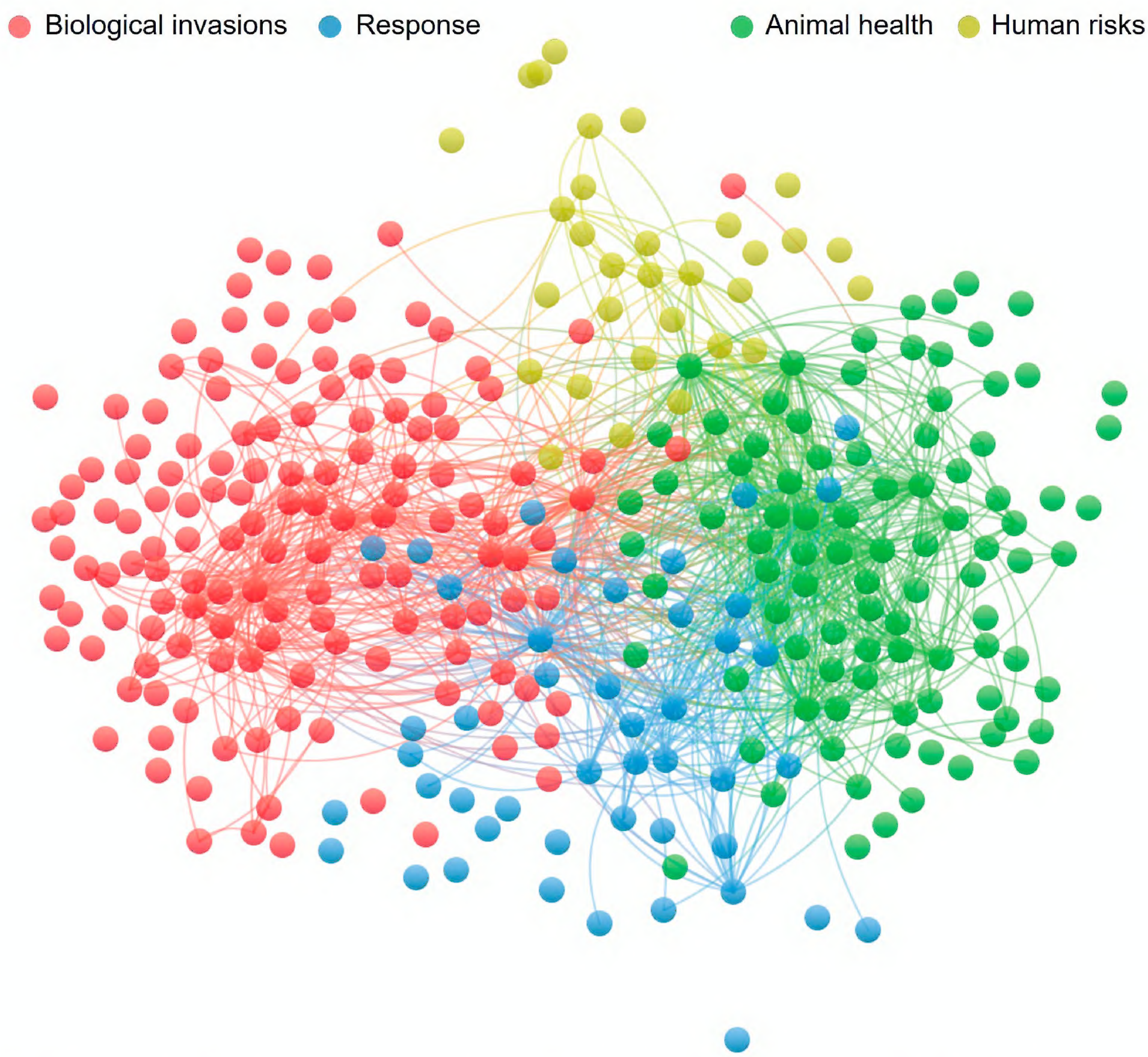

Figure 4. Co-word analysis of 308 terms derived from Keywords Plus that were cited more than five times in articles from the biosecurity corpus published between 2000 and 2022. Four clusters can be identified that relate to animal health (e.g. infection, transmission, epidemiology), biological invasions (e.g. surveillance, spread, invasive alien species), human risks from emerging threats from pathogens (e.g. disease, virus, infectious disease) and the response to biosecurity threats (e.g. management, prevention, policy).

introduction (e.g. pathway, trade, transport, aquaculture) and management (e.g. surveillance, eradication, risk assessment). In contrast, the animal health cluster has a strong representation of the target livestock (pigs, poultry, cattle, equine) and livestock diseases (e.g. foot and mouth disease, African swine fever, avian influenza), as well as management tools (e.g. vaccination, epidemiology, disinfection). The human risks cluster described emerging threats from human activities (e.g. biowarfare, biosafety, dual use research), high profile zoonotic diseases (e.g. Covid-19, Ebola, influenza) and society's response (e.g. public health, One Health, global health security). The response cluster included keywords relating to human perspectives (e.g. perceptions, attitude, behaviour), the importance of engagement (e.g. awareness raising, communication, participation) and subsequent actions (e.g. decision-making, policy, strategies). The association of this cluster with terms, such as veterinary, animal disease and farmer, point to this area being most strongly developed for animal health.

Discussion

Biosecurity is clearly an interdisciplinary subject that encompasses human, animal, plant and ecosystem health, but also requires the involvement of economists, epidemiologists, engineers, policy-makers, public health specialists, social scientists and taxonomists. While this breadth of coverage and underpinning expertise is a strength that underlies the importance of biosecurity to society, the economy and the environment, it is also a weakness that results in multiple interpretations of its core definition. Indeed, many sectors interpret biosecurity only in terms of their own priorities and needs, whether it is in relation to dual use research, quarantine regulations or farm hygiene. As a result, the research landscape is fragmented with the consequence that knowledge is not shared widely and, thus, often fails to bring a sufficient critical mass of expertise to bear upon fundamental aspects of biosecurity that are common to human, animal, plant and ecosystem health (Hulme et al. 2023). Bibliometric analysis is particularly well suited to the analysis of a corpus of research publications and, while the articles in the biosecurity corpus included house journals of policy-making organisations (e.g. EFSA Journal, Revue Scientifique et Technique-Office International des Epizooties), it did not comprehensively review global, regional, national and sector policy documents. While it might be expected that there is cross-fertilisation in terminology across research and policy, the explicit exploration of terminology amongst policy-makers in the future would be valuable. Nevertheless, the comparison of co-citation, bibliographic coupling and co-word analysis provides a unique opportunity to assess the cognitive barriers that are obstacles to an interdisciplinary approach to biosecurity.

Co-citation analysis examines a corpus of articles in terms of its most highly-cited articles and, thus, provides a basis to understand the fundamental aspects of a research field. The co-citation analysis revealed marked segregation amongst research themes that addressed biosecurity, illustrating that the research supporting different sectors largely draws from a distinct literature base. While ecosystem and plant health were clustered together within the broad grouping of biological invasions, there was a clear separation from both human and animal health. Since co-citations reflect the frequency with which two articles are cited together in other documents, the strong clustering and segregation highlights that there is little crossover in the biosecurity relevant literature cited in the study of biological invasions, human health or animal health. Those articles in the human health cluster that had greatest affinity for the biological invasions cluster addressed issues of agro- or bioterrorism (Meyerson and Reaser 2002b; Wheelis et al. 2002), while those with affinity to the animal health cluster addressed generic issues regarding the implementation of biosecurity strategies (FAO 2007; Oidtmann et al. 2011). In addition to the segregation of human health, animal health and biological invasions, articles addressing social perspectives were also separated from the other three clusters. Nevertheless, the social perspectives cluster was more closely aligned to human and animal health than biological invasions and included articles criticising the "emerging disease worldview" of multinational organisations (King 2002) and the governance of biosecurity particularly in relation to animal health (Donaldson 2008; Enticott 2008). The integration of social science perspectives into the study of biological invasions is critical (Ricciardi et al. 2017; Shackleton et al. 2019), but the co-citation

analysis indicates that there is much further to go to achieve this goal. While some articles in the co-citation analysis integrate biological, epidemiological and policy responses to invasive alien species outbreaks (Potter et al. 2011), there is considerable scope for learning from the social perspectives in both human and animal health to better manage biological invasions.

By considering recently-published research that has fewer citations, bibliographic coupling highlights articles that share a common conceptual background and the more references in common, the stronger their connection in a bibliographic network (Zupic and Čater 2015). As it represents recent knowledge, bibliographic coupling highlights articles that are often overlooked in co-citation analysis. Despite this distinction in analytical approach, the results of bibliographic coupling for the corpus of articles addressing biosecurity revealed similar trends as those found for co-citation. The network topology reflected a similar pyramid structure that segregated studies addressing biological invasions (incorporating ecosystem and plant health) from animal health and human health with social perspectives playing a more central role. However, the analysis highlighted subclusters within both the biological invasions and animal health clusters. This might indicate that research is becoming more, rather than less, fragmented in recent years and increasingly draws from a distinct literature base. Within the topic of biological invasions, there were distinct subclusters relating to plant health, pathways and diagnostics while, for the animal health cluster, there were subclusters associated with different animal production systems. Biosecurity issues arising from aquaculture appear to bridge the animal health and biological invasions clusters due to the concerns that pathogens will spread from aquaculture into natural environment and infect wildlife (Bouwmeester et al. 2021; Bray et al. 2024). Social perspectives remain integral to both the human and animal health clusters and there is also evidence that the field of biological invasions has begun to embrace this aspect in the last decade (Tassin and Kull 2015; Head 2017).

Segregation of the human, animal, plant and ecosystem health aspects of biosecurity was also evident when examining keywords. This is in part because of the taxonomic differences between both the biosecurity threats (e.g. plants, microbes, animals) and the recipient target (e.g. humans, livestock, plants). Framing research article keywords along taxonomic lines is clearly valuable to share information within specific topics, particularly for pathogens, but can create a barrier for interdisciplinary communication (Paap et al. 2020). A more effective way to increase interdisciplinary communication across the wide range of biosecurity topics would be to focus on the fundamental processes of species introduction, establishment, spread and impact, as well as the associated responses, such as surveillance, monitoring and control (Hulme 2020). There are clear parallels between the entry and spread of an invasive alien species with the establishment of an epidemic pathogen (Nuñez et al. 2020; Vilà et al. 2021). The challenge is that, even though the process shares many parallels, the terminology used can differ, for example, virulence vs. invasiveness, transmission vs. spread, outbreak vs. incursion, epidemic vs. invasion. In addition, the same term, such as "vector", may be visualised quite differently by invasion biologists (e.g. cargo freighter) and veterinarians (e.g. mosquito) despite the fact that a common definition that encompasses both these perspectives is widely recognised as "any living or non-living carrier that transports living organisms intentionally or unintentionally" (ICES 2005). While comprehensibility is often a challenge to the

collaboration between scientific disciplines within the sectors charged with biosecurity, the different terminology used has sufficient equivalence that scope exists to communicate ideas across all sectors, but only if researchers and policy-makers are prepared to make the effort.

Going forward, there are at least three steps that need to be taken to increase interdisciplinarity within biosecurity. The first, of course, is to develop an agreed definition that encompasses the diverse perspectives of biosecurity since the multiple definitions used today act to entrench research and policy within narrow confines. One such definition could be "the research, procedures and policies that cover the exclusion, eradication or effective management of the risks posed by the introduction of alien plant pests, animal pests and diseases, animal diseases capable of transmission to humans (zoonoses), the release of genetically modified organisms and their products and the management of invasive alien species and genotypes" (Hulme 2020). A common definition will aid researchers and policy-makers understand that, while their own ambit may be focused only on human, animal, plant or ecosystem health, their work contributes to a much wider goal and that lessons can be learnt from other aligned sectors. This is a critical step in developing a global biosecurity community.

The second is to realise that even with the broad definition of biosecurity, scientific practices are often domain specific, which helps researchers solve complex problems in a cognitively manageable way (MacLeod 2018). Yet, increasingly, there is a convergence in underpinning methodologies to support biosecurity. For example, the application of environmental DNA and RNA for tracing species, the opportunity to apply new technologies for remote surveillance of human, animal, plant and ecosystem health and their associated threats, state-of-the-art decision support tools that provide information for the cost-benefits of different management strategies and social-science approaches that can lead to behaviour change and/or better engagement with communities to foster greater compliance with biosecurity regulations (Hulme et al. 2023). Funding bodies should, therefore, aim to support research that advances broader underpinning issues relevant to more than one sector rather investing solely in taxonomically or sector-focused problems since this will create a greater critical mass of expertise and often result in more effective solutions (Kenna and Berche 2011). Having separate funding bodies for human, animal, plant and ecosystem health is a major barrier to interdisciplinary biosecurity.

Third, with an agreed definition of biosecurity and opportunities to fund interdisciplinary research programmes, the final step is to develop a culture of interdisciplinary thinking in biosecurity. There is considerable opportunity to establish interdisciplinary centres with a focus on biosecurity since it is a subject that is socially relevant and addresses real-world problems that require outputs to support practical actions or interventions. This should encourage researchers to work towards the common good rather than for personal benefits and reputations. Such centres should have a focus on the unity of knowledge, include different disciplines of academic research, involve non-academic participants, such as policy-makers and have a process of continual review to contemplate the broader context of the work (Lawrence et al. 2022). While integration of social science is often promoted as important for interdisciplinary research, the citation analyses indicated that there is already an established community of social scientists working on the socio-political and behavioural aspects of human and animal health. It would seem

sensible to encourage them to extend their skillset to both plant and ecosystem health. In addition, the training of the next generation of biosecurity researchers and policy-makers should embrace interdisciplinarity and to do so will require undergraduate and postgraduate education to emphasise the common elements of the biosecurity system, including the similarities in the processes underpinning invasions and outbreaks (Ogden et al. 2019), their societal impacts (Diagne et al. 2021), shared modelling frameworks (Hulme et al. 2020) and management options. This is a quite different philosophy to previous suggestions for training curricula that have emphasised specialisation within a single sector (Minehata et al. 2013; Moritz et al. 2020) or a strong focus on the development of taxonomic skills (Harmon et al. 2022). While knowledge of pathogens, pests and weeds is an essential basis for biosecurity training, greater emphasis on the fundamental conceptual issues underpinning human, animal, plant and ecosystem health is more important for achieving interdisciplinary thinking.

Conclusions

Bibliometric analyses highlight that the field of biosecurity encompasses a wide range of domains from ecology through to economics and requires an interdisciplinary approach to secure human, animal, plant and ecosystem health. Yet, despite a considerable corpus of research addressing biosecurity, the field remains divided by conceptual differences and specialised vocabularies. This situation limits the effectiveness of biosecurity policies and is increasingly being recognised as an obstacle to effective biodiversity conservation, public health and food security. To overcome these constraints requires the building of a global biosecurity community that accepts a broader definition of biosecurity, avoids sectorial jargon and establishes mechanisms to cultivate interdisciplinarity through specialised collaborative centres, cross-sectorial research programmes and conceptually rich training programmes.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

PEH conceived, analysed, and wrote the paper.

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Data availability

The original data for this research are available through the Clarivate Web of Science.

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